Depth Measurement in a Germanium Strip Detector

E. A. Wulf, J. Ampe, W. N. Johnson, R. A. Kroeger, J. D. Kurfess and B. F. Phlips

Abstract— **We have demonstrated the ability to determine the depth of a gamma-ray interaction point over the full active volume of a thick germanium strip detector. This capability provides depth resolution of less than 0.5 mm FWHM at 122 keV in a device 11mm thick with 2 mm strip pitch. Fifty channels of electronics have been developed and tested with a 25 x 25 germanium orthogonal strip detectors. Experiments examining the capabilities of the system and demonstrating a simple Compton telescope using a single detector have been performed.**

I. Introduction

Germanium strip detectors combine excellent energy resolution for gamma ray detection with good two dimensional resolution. With the addition of depth information these detectors have excellent overall position resolution. Orthogonal strips on the front and rear faces of the crystal allow germanium strip detectors to locate a gamma-ray interaction in two dimensions accurate to the width of the strips. A gamma ray interacts in the crystal and its position is determined by the intersection of the triggered strips on opposite sides of the detector [1]. The depth of the interaction is determined by looking at the timing difference between signals from collection of holes on one side of the detector and electrons on the other side as was recently demonstrated by [2] and [3]. The excellent energy resolution of germanium detectors makes it possible to determine if the signals collected at the front and back are from the same gamma-ray interaction. A germanium detector with sub-millimeter resolution in three dimensions is of interest in gamma-ray astrophysics for the next generation of instruments. It should also have the potential to improve the resolution of Positron Emission Tomography [4]. Another application is for the GRETA detector under study for use in nuclear physics experiments by the Department of Energy [5].

The detector used for this work and the work of [2] is a 25 x 25 germanium orthogonal strip detector with 0.2 cm strip pitch that is 5 x 5 x 1.1 cm deep [1]. It has lithium strips held at +1.5 kV bias potential that collect electrons and boron strips on the opposite face to collect the holes.

The interaction depth is directly related to the time difference between when the electron and hole signals are collected on opposite sides of the detector. This can be seen in Fig. 1 which shows that for an event occurring near the boron face of the detector it takes 113 ns for the electrons to travel to the lithium face. The simplest way to conceptualize measuring the time difference between charge collection is to determine the difference between the times when each of the preamplified signals crosses 50% of its total value. The timing difference in a 1.1 cm thick detector is approximately ±120 ns for conversion near the front or the back of the detector.

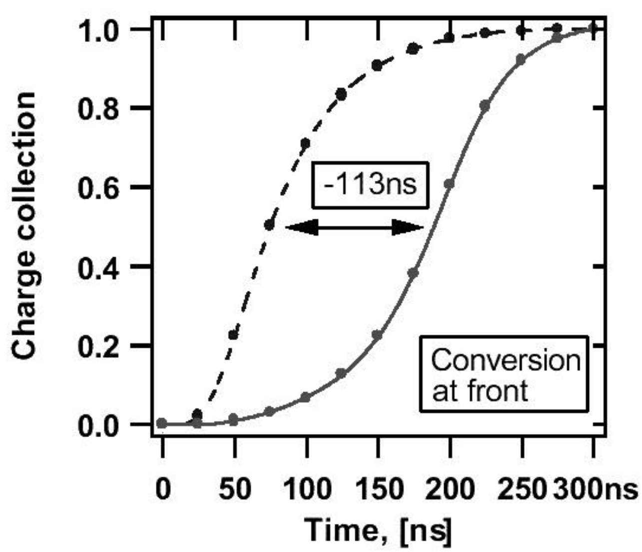

Fig. 1. The digitized preamplified signals from a germanium strip detector. The dashed curve is the signal as holes are collected on the boron side of the detector which is closest to the ^{241}Am source. The solid curve is from the lithium side as the electrons are collected. There is a 113 ns difference in the time when the signals reach their midpoint. This work was published in [2].

II. Electronics

To instrument a detector for depth information, one must determine the time difference between charge collection as well as the energy of the interaction. To determine the energy of an interaction, shaping amplifiers and Analog to Digital Converters (ADC) are needed for all 50 strips. The depth determination requires a discriminator on each of the strips on the front and back of the detector and

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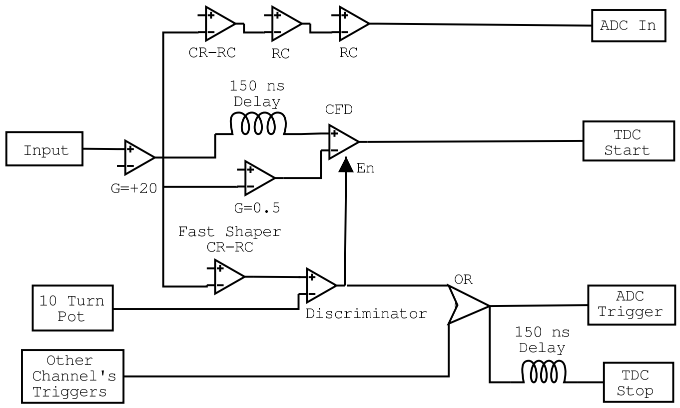

Fig. 2. A schematic of the NIM electronics constructed at NRL and used to instrument the 25x25 germanium strip detector.

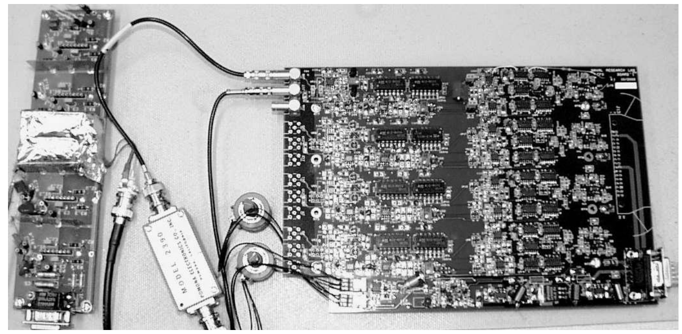

Fig. 3. A picture of one of the NRL electronics boards with four channels. Four of these boards are packaged together to produce one double wide NIM module. The module to the left is a board holding multiple eV5093 preamplifiers that were used to produce test signals.

a Time to Digital Converter (TDC) or the equivalent to measure the relative timing of the signals.

A major design question is whether a Constant Fraction Discriminator (CFD) is necessary or if a simple Leading Edge Discriminator (LED) is adequate for the relative timing of the signal rise. One type of CFD works by making two copies of the input signal, inverting and delaying one copy, attenuating the amplitude of the other and adding the two signals. This creates a zero crossing that occurs when the original signal was a fixed percentage of its full value. This is useful for eliminating time walk as a function of amplitude. The problem with CFDs in this application is that 150 ns of delay are necessary. This may be difficult to implement in future compact, low power electronics. In contrast, an LED triggers when the input signal goes over a specific voltage and therefore can trigger at different times for different pulse amplitudes. This may not be a large issue for the germanium strip detector because the amplitude of the signals on the front and back of the detector are the same and the time walk is expected to be similar.

To read out all 50 strips on the detector with both energy and depth information requires 50 channels of shaping amplifiers, 50 channels of discriminators, 50 channels of ADCs, and 50 TDC channels. A decision was made to create a NIM module that incorporated the shaping and discriminator functions in order to reduce the total number of modules. The outputs from eV5093 preamplifiers are fed into a buffer amplifier with a gain of 20 (see Fig. 2). The signal is then split and one copy is shaped by a four pole shaper with a fixed gain, and is fed to an ADC. Another copy of the amplified preamplifier signal goes to a fast shaper with an integration and differentiation time of 50 ns. The output of the fast shaper is run to a discriminator and compared to a DC level set by a front panel potentiometer. The output of the discriminator is summed with all other channels and used as a master trigger to start the ADC and as a common stop for the TDC. Another copy of the discriminator output is used to enable the comparator used in the CFD electronics.

The CFD section is composed of two copies of the amplified preamplifier signal. One copy is delayed by 150 ns and the other is attenuated to 50% of its original amplitude. These two signals are fed into a comparator that fires when the two signals have the same amplitude. In effect, this produces a signal when the preamplifier signal has risen to half of its total value. The CFD signal is used to start a TDC channel for each front and back strip.

Each electronics board supports four detector channels and four boards are included in one double wide NIM module (see Fig. 3). The outputs from these modules are fed into TDCs and ADCs residing in a CAMAC crate which is read out by a PC running Linux. The data is recorded on an event by event basis and saved to disk and tape for later analysis. This system maintains the excellent energy resolution, 1.6 keV at 122 keV, of a germanium detector as can be seen from a typical ^{57}Co spectrum in Fig. 4.

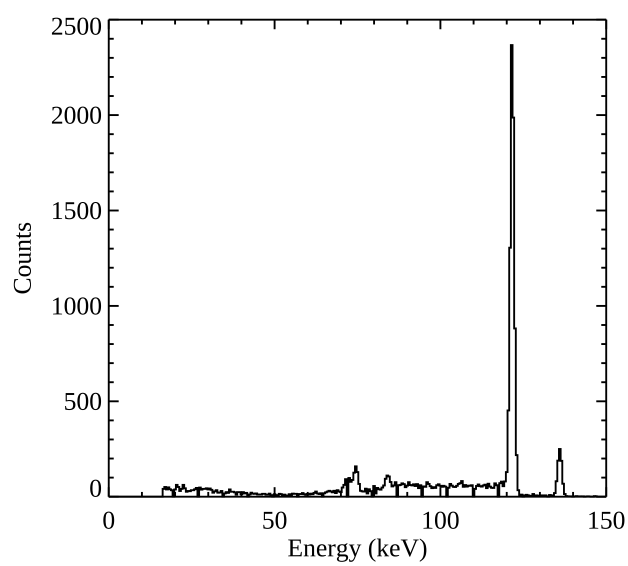

Fig. 4. Spectrum of ^{57}Co source as measured with the germanium strip detector and the NIM electronics.

III. Depth Measurements

A. Detector Attenuation

The depth capabilities of the detector are demonstrated by observing the attenuation of gamma rays as they pass through the detector. These tests confirmed that the depth of the interaction could be measured but are not an accurate way to determine the actual depth resolution of the system. The attenuation experiment was done by placing a source near the boron face of the detector and producing a histogram of the time difference in charge collection between the boron and lithium face. Each event histogramed had to have only one strip with a signal on both the lithium and boron side and each signal had to be the correct energy to within 5 keV.

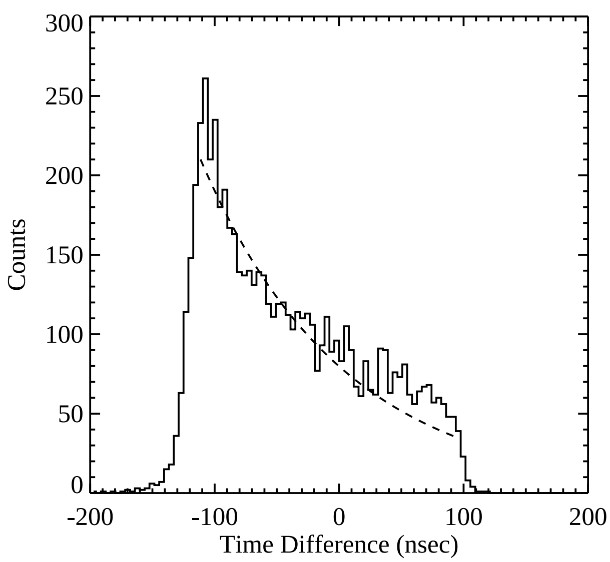

Fig. 5. The number of photo-peak events for the 122 keV gamma ray line from ^{57}Co as a function of time difference between charge collection on the boron and lithium face. The source was placed 40 cm from the boron face of the detector. The dashed line is the theoretical exponential attenuation of the gamma rays by the germanium that makes up the detector.

^{57}Co has a 122 keV gamma-ray line that is attenuated 85% by the detector volume. The radiation length is 5.75 mm which is approximately half the detector thickness. A plot of the number of counts as a function of time difference between charge collection on the front and back face is shown in Fig. 5. The face of the detector that was closest to the source was the boron face which corresponds to negative time differences and the lithium face to positive differences. The theoretical exponential attenuation of the germanium is shown superimposed as the dashed line on the plot. The total time difference is shown to be 215 ns for the 1.1 cm thick detector. This is similar to the total time difference found by [2]. The 15 ns difference between hole collection on the boron side and electron collection on the lithium side is due to the difference in drift velocities in germanium. At the detector's bias voltage of 1500 V and a temperature of 80K, the drift velocity of the holes is 7.5 x 10^6 cm/s, and that of the electrons is 8.3 x 10^6 cm/s [6]. Using a detector thickness of 1.1 cm yields a total time difference that is larger than observed by 25%. This suggests a small nonlinearity in depth timing near the surfaces. The experiment was also performed with ^{241}Am and ^{137}Cs which showed good agreement with the theoretical exponential attenuation curves. The differences between the attenuation curve and the measured values are most probably due to variations in the electric field near the surfaces of the detector, variations in the contaminants in the germanium, and not being able to sort out pure photoelectric events.

B. Fan Source Scan

To test the depth resolution of the detector, the side of the detector was illuminated with a tightly collimated gamma-ray beam. A 1 mCi ^{57}Co source was mounted in a collimator consisting of two flat planes of tantalum approximately 11.5 cm in length and 2 cm thick. The two planes are separated by 0.1 mm thick spacers. This produces a well defined fan beam useful for scanning the detector. The fan source was scanned along the side of the detector using an x-y position table. The table has a position resolution of 0.025 mm and a range of 10.2 cm. The source was moved in 0.5 mm steps and data was collected at each point along the side of the detector.

A histogram of the timing difference between charge collection on each boron strip and any lithium strip was constructed. For each event, only one lithium and one boron strip could have a signal and their energies had to be within 5 keV of the 122 keV line. One boron strip in the middle of the detector was selected and the time difference for each position was plotted (see Fig. 6).

Based on a linear regression of the centroids for each position, the detector is shown to have an integral nonlinearity of 5.7% across the detector. This slight nonlinearity is probably due to changes in the electric field near the electrode structures on the faces.

The time resolution of the system for the fan beam illuminating one position on the side of the detector is 14 ns FWHM. This corresponds to 0.70 mm for this detector. The gamma ray beam is 0.15 mm wide at the edge of the detector and the average electron motion at this energy is 0.1 mm. Subtracting these contributions in quadrature from the overall resolution of 0.70 mm yields a depth resolution of 0.68 $\pm$ 0.09 mm FWHM.

IV. Single Detector Compton Telescope

Having three dimensional readout of a germanium strip detector gives good position resolution in all three-dimensions and excellent energy resolution. This allows one to use a single detector as a Compton telescope, as opposed to the traditional configuration using two separate detectors in coincidence to measure two interactions.

Consider gamma rays coming from a point source. Some of these gamma rays will Compton scatter in one location in the detector and then interact a second time at a second location in the same detector, depositing all of their energy

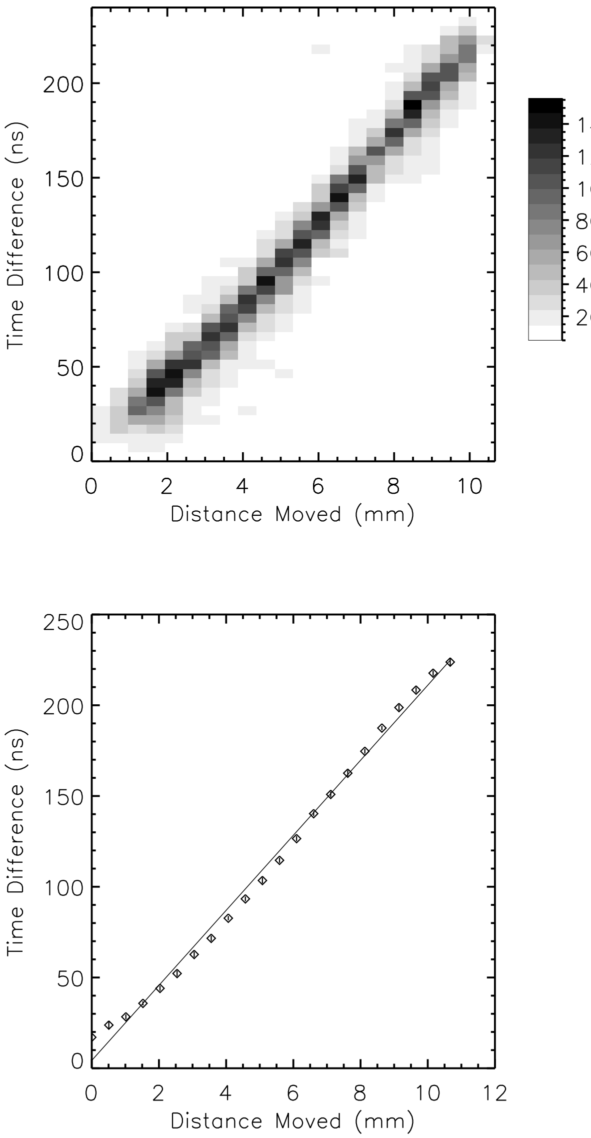

Fig. 6. A fan beam scanned across the side of the detector from the lithium side to the boron side. The x-axis is the actual position of the source on the translation table and y-axis is the depth of the interaction determined by taking the time difference in charge collection. The lower left hand corner corresponds to the front of the lithium face and the upper right hand corner to the front of the boron face. The bottom plot shows the location of the centroid for each position and a linear regression of the centroids. The error on the centroid is less than the diameter of the points.

in these two interactions. The Compton scattering angle in the first interaction can then be determined from the Compton Formula

$$\cos\theta = 1 - \left(\frac{m_e c^2}{E_1 + E_2}\right)\left(\frac{E_1}{E_2}\right) \qquad (1)$$

where θ is the Compton scattering angle, m_e is the electron rest mass, and E_1 and E_2 are the energies in keV deposited at the two interaction points. Knowing the position of the two interaction points can then be used to draw a cone of possible directions from which the gamma ray source must be located. Drawing enough of these cones and determining the intersection point reconstructs an image of the gamma ray source.

This experiment was done with a 8.8 μCi ^{22}Na source placed 41 cm from the boron side of the detector and a 1.3 μCi ^{137}Cs source 20 cm to the left of the ^{22}Na. The data was acquired for 45 minutes. Events that had two strips with signals on the boron side and two strips hit on the lithium side that added up to either 662 keV or 511 keV were selected. These events were then checked to make sure that each hit on the boron side had an exact energy match with a strip on the lithium side and that events were not in neighboring strips. This data set was then used to reconstruct the image using a simple ring sum algorithm.

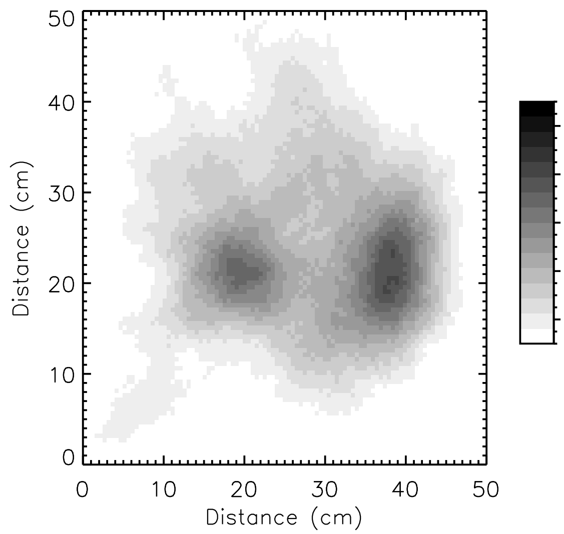

Fig. 7. A reconstructed image of a ^{137}Cs and ^{22}Na source placed 41 cm from the boron face of the detector and separated by 20 cm. A Compton ring for each event was drawn at a distance of 41 cm from the front face of the detector and summed together to produce this image.

Each point on a plane located 41 cm from the detector was tested to see if it satisfied the Compton scattering formula within errors using the position and energy information from the event. Each pixel that satisfied these requirements was given a value weighted by the total number of pixels for each event. This was done for both orderings of the event since the true ordering is not always known. All events were then summed together which produced the image shown in Fig. 7. A similar image was produced when knowledge of the sources positions were used to determine the correct event ordering.

Both sources are visible in the image and are separated by 20 cm. The ^{137}Cs has better angular resolution because it has the higher gamma-ray energy. The position resolution is about 5 cm which corresponds to 7° angular resolution. This image would have been impossible without the depth resolution because the interaction point would only have been defined by the overlapping front and back strips.

V. Timing Methods

All of the experiments in the previous section used the electronics diagramed in Fig. 2. The TDCs were started by the CFD signals from our custom NIM boards and stopped by a delayed copy of the LED. To determine if the depth resolution measured in the preceding sections is limited by the detector or the electronics, the depth resolution was measured using different electronics setups. Commercial NIM modules were used to test these other timing methods due to their flexibility and ease of wiring. Due to channel limitations, only one lithium strip and three boron strips were instrumented.

The CFDs implemented on our custom boards could be limiting the timing resolution of the system. To determine if this is the case, preamplifier signals were fed into Ortec Timing Filter Amplifiers (TFA) set to 200 ns differentiation and integration time. The TFA's signal is sent to an Ortec CFD with 150 ns of external delay. The timing signals from the CFDs start the TDC channels, gate the ADCs, and, after being delayed, stop the TDC. To measure the timing resolution of this system, a ^{57}Co fan beam illuminated a fixed position on the side of the detector which was 4.5 mm from the lithium face. This beam illuminated all of the horizontal boron strips and, due to attenuation, the first few lithium vertical strips. Using this electronics setup, the timing resolution was 9 ns which corresponds to 0.45 mm depth resolution. Taking into account the beam width and electron motion, this system has a depth resolution of 0.41 ± 0.08 mm which is better than the 0.68 ± 0.09 mm resolution with the CFDs on our custom boards. The lower performance of the custom build electronics is probably due to jitter or noise in the design. Further tests will need to be done to determine the exact cause of the problem.

Replacing the Ortec CFDs with LEDs and setting the triggering threshold to 20 keV resulted in a timing resolution of 9 ns FWHM as well. A comparison of the depth resolution for this configuration and for the configuration with the custom built NIM modules is shown in Fig. 8.

The LED worked as well as the CFD for the 122 keV gamma ray line but it is not known at this point if it would have the same resolution at a range of different energies. There are many other methods to determine timing accurately without the need for a delay line. One that we have implemented and will be testing soon uses a comparator to look at the crossing between the fast shaped preamplifier signal and the integral of the fast shaped signal [7]. This timing circuit has been produced in CMOS which would be useful for producing an ASIC that combines a shaped signal and timing information for an entire detector. All of these methods will be investigated further at a variety of energies.

VI. Multiple Interactions

As the gamma-ray energy increases, the likelihood of the gamma ray depositing all of its energy in one pixel decreases. At a gamma-ray energy of 662 keV from a ^{137}Cs source, the photo-peak efficiency in the germanium detector is less than 1%. The rest of the events will involve Compton scattering and charge sharing with neighboring strips. Depth information should be able to distinguish between these two types of events. This would allow charge sharing events to be used in event reconstruction using the average position and the sum of the energies in the two strips. The Compton scattering events would then be available for reconstruction. This increases the efficiency of the detector by allowing more event types to be used in the final analysis.

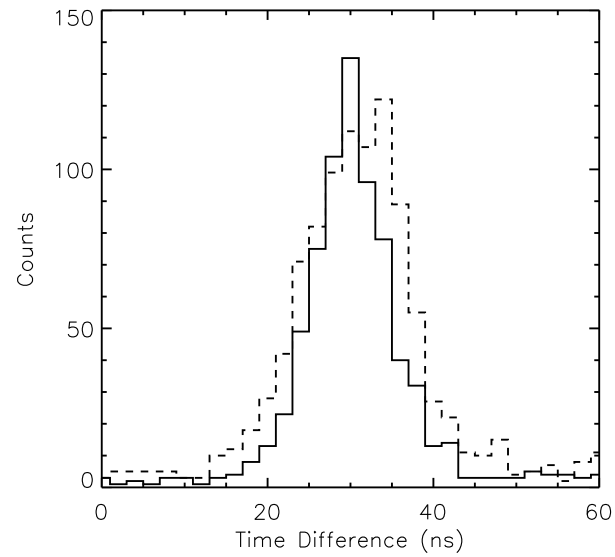

Fig. 8. The solid curve is the time difference between charge collection on the boron and lithium sides of the detector using a LED to determine timing. The dashed curve is the time difference using the integrated NIM electronics used for the other experiments.

To look at depth information in neighboring strips, a ^{137}Cs source was placed 41 cm from the detectors boron side. Events were selected that had only one signal on the boron side and two neighboring strips hit on the lithium side. The time difference between the two neighboring strips on the lithium side was histogramed. Charge sharing events should have essentially no time difference and Compton events should have a variety of time differences based on where the interactions occurred. Charge sharing events should be independent of source position while Compton scattering should be affected by source location because this movement causes changes in the scattering angles between the strips. This was all seen in the experiment as shown in Fig. 9. There is a center peak, charge sharing events, that was unaffected by source position and then Compton events that shifted with changing source position. More work is necessary to make this technique useful for distinguishing between different event types.

VII. Conclusions

The depth of a gamma ray interaction can be measured in an orthogonal germanium strip detector to less than 0.5

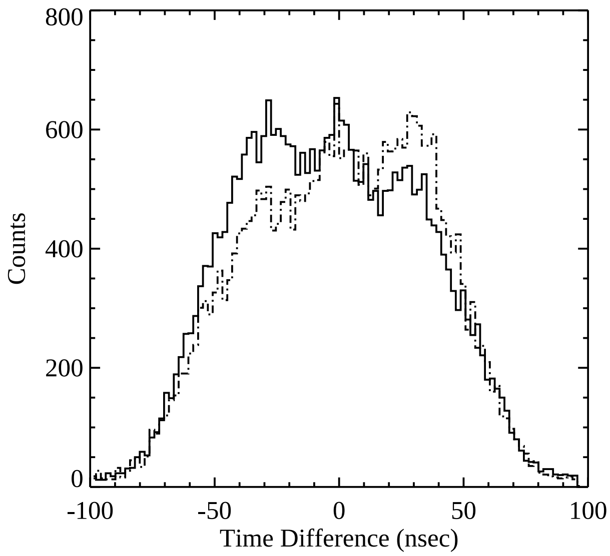

Fig. 9. A ^{137}Cs source was used to illuminate the detector at two different points separated by 20 cm at a distance of 41 cm from the boron face of the detector. The time difference between neighboring strip hits on the lithium side is histogramed. The solid line is for the source centered with the detector and the dashed line is for the source located 20 cm above the center.

mm. The depth information coupled with the x-y position information from the strips yields a detector that is useful for a number of ground and space based instruments. Compton telescopes built from detectors with three dimensional readout would have better image and energy reconstruction. Also, this enables the use of thicker detectors which would lead to less electronics for the same amount of detector volume.

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